FORM 2

THE PATENTS ACT, 1970
(39 of 1970)
AND
THE PATENTS RULES, 2003

COMPLETE SPECIFICATION

(See section 10; rule 13)

TITLE OF THE INVENTION

"LUNAR SOIL SIMULANT AND A PROCESS FOR ITS MANUFACTURE"

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The following specification particularly describes
the invention and the manner
in which it is to be performed

LUNAR SOIL SIMULANT AND A PROCESS FOR ITS MANUFACTURE

FIELD OF INVENTION

The present invention relates to a lunar soil simulant prepared from a terrestrial analogue and a method for producing and manufacturing it. The lunar soil simulant can be used for scientific studies of lunar terrain relating to mobility/ trafficability of rover for scientific explorations or for the study of geo-technical/ mechanical properties of lunar soil for understanding the engineering behavior of lunar regolith or to carry out fundamental research work (theoretical and experimental) to postulate a broad design philosophy for realizing civil engineering structures on Moon surface, and to make a pathway to lunar locomotive engineering.

BACKGROUND OF INVENTION

Since the announcement in 2004 of a new vision for the United States Space Exploration programme, lunar exploration has become one of the most pressing global scientific problems to be tackled, so that the Moon could be the "Launch pad" for further space exploration and inter-planetary engineering. Various scientific organizations and engineering fields including civil, mechanical and chemical etc are expected to be involved in this universal program in view of ***"future Moon colonisation"***. Lunar exploration requires a full understanding of the physical and chemical properties of lunar surface soil as most of the building materials have to be produced out of the regolith for human settlement on the Moon. The limited amount of actual lunar soil samples retrieved during the Apollo missions will not facilitate to conduct such extensive research works. Moreover, terrain facilities similar to lunar surface is required to test rovers and Lander to avoid any risk of failure. Hence there exists a compelling need to manufacture/ produce lunar soil simulants on the earth to carry out necessary pioneering research works.

Compositionally, the lunar soils fall into two broad groups; the *highland soils*, which are developed on anorthositic bedrock and *mare soils*, which are developed on basaltic bedrock. Mare soils can be further sub-classified as to high or low titanium

content soils. Highland soils are relatively enriched in aluminium and calcium, while mare soils are relatively enriched in iron, magnesium, and titanium (*Allton et al., 1985*). The use of lunar simulants is focused on physical characteristics of the lunar regolith for undertaking landing and transportation activities.

There are more than 30 lunar simulants that have been produced to date, some of which have been exhausted. **JSC-1** is a lunar regolith simulant that simulates a soil that is poor in titanium. It is a basaltic ash with high glass content. **JSC-1A** standard lunar mare regolith simulant is a lower particle size simulant mined from a volcanic ash deposit located in the San Francisco volcano field near Flagstaff, Arizona, and has a grain size of 1mm or lower. **MLS-1** is a lunar simulant that was developed at the University of Minnesota. The basaltic rock used in this simulant was mined from a quarry in Duluth, Minnesota. It contains plagioclase, olivine, pyroxene and ilmenite as some of its major minerals. The minerals and grain sizes resemble the chemistry of the Apollo 11 mare material. **FJS-1** and **Kohyamal lunar soil simulants** are made of basalts of Mt.Fuji, and gabbro in Kohyama in Japan respectively. Oshima is made of basalt containing volcanic glass with addition of 7 wt% forsterite and 8 wt% ilmenite to mimic the chemical components of lunar regolith in high Ti mare region *(Sueyoshi et al., 2008)*. **CAS-1**, a new lunar soil simulant prepared by Chinese Academy of Sciences is being used to support lunar orbiter of soft-landing mission and sample return mission of China's Lunar Exploration Program, which is scheduled during 2004-2020 *(Yongchun et al., 2009)*. The source material for this simulant was low-Ti basalt scoria from later Quaternary volcanic area Changbai Mountains of China.

Apart from the above, several attempts have been made in the past in this field to reproduce the lunar environment for research purposes. For Example, US5348696 discloses chemical processing by hydrogen reduction of lunar ilmenite and agglutinates with particle size in the range of 20-200 microns. US8066796 discloses a method of creating simulated agglutinate particles by applying a heat source sufficient to partially melt raw material like crust minerals etc. US8283172 discloses a metallurgical process consisting of mixture of ferric chloride, fluorinated carbon

powder and glass beads to produce a nanophase iron to prepare lunar soil simulant dust.

US4948477 discloses a manufacturing plant and process for production of oxygen on the Moon using lunar minerals as feed and minimum of earth imported process materials. It deals with detailed chemical/ metallurgical manufacturing process.

CN102115321 discloses a material of simulated lunar soil, which comprises 60-95 wt% of Beijing Zhuzhuang dry silt with a particle size of less than 5 mm and 5-40 wt% of Hebei Lingshou garnet powder with a particle size of less than 5 mm. The simulant produced by the process disclosed in this document is prepared from easily available raw materials which satisfies their rover testing requirements, otherwise the simulant is not analogous with mineralogy, chemistry and particle size of the actual lunar soil.

CN102589910 discloses a lunar soil and lunar appearance simulation system comprising a simulated lunar soil horizontal region, a simulated lunar soil slope region, a simulated lunar crater, wherein the regions are constructed by simulated lunar soil for simulating actual lunar soil mechanical property. Proportioned volcanic ash, i.e., a homogeneous material, of different particle sizes is adopted to simulate lunar soil according to the requirements of the rover.

CN101957280 discloses a method for preparing simulative lunar soil comprising the steps of selecting and collecting source rock samples, pulverizing the collected source rock samples and selecting the source rock samples with a certain precision from the pulverized source rock samples; sintering the prepared initial samples of the simulative lunar soil into glass; and pulverizing the sintered glass and then mixing the pulverized glass and the prepared initial samples of the simulative lunar soil in a certain ratio to obtain the simulative lunar soil. Although the process disclosed in this document provides a method of preparation of lunar soil simulant

representing lunar mare basalt and highland region, it is not clear that whether two separate simulants developed for two different regions. The highland returned samples represent at least five ranges of particle size in the regolith, which is not addressed in the invention.

JP2003021580 disclose a process to provide lunar-regolith simulated soil employing silt of hard rocks such as granite, basalt, andesite or the like and coarse sand as well as river sand and/or mountain sand by adjusting their engineering characteristic to that of lunar regolith. The lunar simulant herein is produced from a mixture of rock materials and river sands, which may not fit close to the lunar regolith.

The simulants disclosed in the prior art documents mostly represent lunar mare region, which represents only 17% of the lunar crust. Various countries produced simulants either based on their own research need or the availability of source rocks.

A number of other patents are found in the literature with regard to chemical processing and metallurgical processing applied for various minerals at high temperatures etc., to produce certain new artificial compounds to simulate lunar dust. A brief list of such patents include, for Example, US3210180, US4224056, US3637368, US3295956, US3346365, US3554733, US3374087, US3896560, US4439929, US3993653, US3464861, US4087976 .

Various natural and man-made materials have been used as feedstock for the simulants from crushed volcanic tuffs with abundant glass (e.g., JSC-1 and JSC-1A), to anorthosite with added fayalitic (Fe silicate) slag (e.g., OB-1), to synthetic agglutinates, to synthetic nanophase metallic iron (FeO). Although some of the simulants produced to date have served well for important studies and tests, other simulants do not have the proper lunar soil properties for which they have been applied or utilized.

Support for upcoming lunar polar missions requires identification, assessment and development of both mare and highland simulants *(Sibille et al 2006)*. Simulants currently offered are exceedingly variable in all properties and available quantity, as well as fidelity when compared to actual lunar regolith. Some simulants are more suitable for specific tasks than others. That is, a successful geotechnical simulant is generally not also prudent for geochemical or mineralogical tests. It is difficult, expensive, and time-consuming to produce adequate simulants. Hence, there is a need for new simulants for diverse lunar applications which provides the lowest possible mission risk, and can be produced at much lower price.

There is a need for lunar simulants with more accurately produced lunar regolith properties (known as higher fidelity simulants), especially in view of the more lunar properties that are involved/required for specific tests. The present inventors have noticed that the most challenging task is to simulate the mechanical and geotechnical properties of the lunar soil with mixing of appropriate ratio of various grain size materials. The present invention is directed to such a cause, where the inventors have ingeniously arrived at a method which provides a lunar simulant which not only has its chemical and mineralogical composition similar to the lunar soil, but the mechanical and geotechnical properties of the simulant are also strikingly similar. The method used for preparing the lunar simulant of the present invention is cost effective and reproducible and is easy to practice and scale up.

The lunar highland crust comprises of high calcium plagioclase (80-95%) than almost any terrestrial plagioclase and a simulant which is close to lunar plagioclase composition is viewed as a significant marker of simulant fidelity. In the simulant of the present invention, the average ratio of plagioclase in the simulant is 89% (from anorthositic rock), which is almost close to the lunar composition.

Most of the countries produced simulants representing lunar mare region. The lunar highland crust occupies 83% of the lunar surface, however only limited number simulants represent regolith of lunar highland region. Most of the future missions

propose for soft landing on lunar highland region. Hence, there is an urgent need for bulk quantity of lunar soil simulant, which represent highland lunar crust. The lunar soil simulant of the present invention is exclusively manufactured to represent lunar highland region. The regolith of lunar highland region is mainly derived from anorthositic rock formation. The present simulant produced and manufactured in bulk quantity exactly from similar rock samples identified and picked out from Sittampundi Anorthosite Complex, India. Moreover, the invention satisfied all aspects including mineralogy, bulk chemistry, grain size distribution and geo-mechanical properties.

SUMMARY OF INVENTION

One aspect of the present invention relates to a lunar soil simulant obtained from a terrestrial analogue having 40-50% of SiO_2, 20 to 40 % of Al_2O_3, 10 to 20% of CaO, and plagioclase, pyroxene as the major mineral components, characterized in that

40-50% of the soil particles have a particle size distribution of 30-80µm,

15-20% of the soil particles have a particle size distribution of 80-150µm,

15-20% of the soil particles have a particle size distribution of 150-300µm,

15-20% of the soil particles have a particle size distribution of 300-600µm,

15-20% of the soil particles have a particle size distribution of 600-1000µm

Another aspect of the present invention provides a process for the manufacture of lunar soil simulant (LSS) comprising the steps of:

a) Obtaining terrestrial rock samples having 40-50% of SiO_2, 20 to 40 % of Al_2O_3, 10 to 20% of CaO, and plagioclase, pyroxene as the major mineral components;

b) pulverising the material into gradations of 30-80 microns/ 80-150 microns/ 150-300 microns/ 300-600 microns/ 600-1000 microns; and

c) Mixing the samples of different gradations/fineness in specific ratios.

Further scope and applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating embodiments of the invention, are given by way of illustration only, because various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as claimed.

DETAILED DESCRIPTION

For the purposes of the following detailed description, it is to be understood that the invention may assume various alternative variations and step sequences, except where expressly specified to the contrary. Moreover, other than in any operating examples, or where otherwise indicated, all numbers expressing, for example, quantities of ingredients used in the specification are to be understood as being modified in all instances by the term "about". It is noted that, unless otherwise stated, all percentages given in this specification and appended claims refer to percentages by weight of the total composition.

Thus, before describing the present invention in detail, it is to be understood that this invention is not limited to particularly exemplified systems or process parameters that may of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments of the invention only, and is not intended to limit the scope of the invention in any manner.

The use of examples anywhere in this specification including examples of any terms discussed herein is illustrative only, and in no way limits the scope and meaning of the invention or of any exemplified term. Likewise, the invention is not limited to various embodiments given in this specification.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention pertains. In the case of conflict, the present document, including definitions will control.

It must be noted that, as used in this specification and the appended claims, the singular forms “a,” “an” and “the” include plural referents unless the content clearly dictates otherwise. Thus, for example, reference to a “polymer” may include two or more such polymers.

The terms “preferred” and “preferably” refer to embodiments of the invention that may afford certain benefits, under certain circumstances. However, other embodiments may also be preferred, under the same or other circumstances. Furthermore, the recitation of one or more preferred embodiments does not imply that other embodiments are not useful, and is not intended to exclude other embodiments from the scope of the invention.

As used herein, the terms “comprising” “including,” “having,” “containing,” “involving,” and the like are to be understood to be open-ended, i.e., to mean including but not limited to.

As used herein the term “Anorthosite rock” refers to a phaneritic, intrusive igneous rock characterized by a predominance of plagioclase feldspar (90–100%), and a minimal mafic component (0–10%). Pyroxene, ilmenite, magnetite, and olivine are the mafic minerals most commonly present.

As used herein, the term “Lunar simulants” intends to mean any material manufactured from natural or synthetic terrestrial or meteoritic components for the purpose of simulating one or more physical and/or chemical properties of a lunar rock or soil’.

As used herein, the term “Lunar soil” is the fine fraction of the regolith found on the surface of the Moon. Its properties can differ significantly from those of terrestrial soil. The physical properties of lunar soil are primarily the result of mechanical disintegration of basaltic and anorthositic rock, caused by continuous meteoric impact and bombardment by interstellar charged atomic particles over billions of years.

As used herein, the term “regolith” intends to mean a layer of loose, heterogeneous material covering solid rock at Moon. It includes dust, soil, broken rock, and other related materials. Regolith covers almost the entire lunar surface, bedrock protruding only on very steep-sided crater walls and the occasional lava channel. This regolith has formed over the last 4.6 billion years from the impact of large and small meteoroids, from the steady bombardment of micrometeoroids and from solar and galactic charged particles breaking down surface rocks.

As used herein, the term “phaneric” intends to mean visibly crystalline; phanerocrystalline compound. This term is applied to crystals which are visible without the aid of a magnifying-glass.

One aspect of the present invention relates to a lunar soil simulant obtained from a terrestrial analogue having 40-50% of SiO_2, 20 to 40 % of Al_2O_3, 10 to 20% of CaO, and plagioclase, pyroxene as the major mineral components, characterized in that

40-50% of the soil particles have a particle size distribution of 30-80µm,
15-20% of the soil particles have a particle size distribution of 80-150µm,
15-20% of the soil particles have a particle size distribution of 150-300µm,
15-20% of the soil particles have a particle size distribution of 300-600µm,
15-20% of the soil particles have a particle size distribution of 600-1000µm

In an embodiment, the terrestrial analogue is an anorthosite rock with percentage of major oxides, particularly $SiO_{2,}$ Al_2O_3 and CaO equivalent to 40-50% of

SiO_2, 20 to 40 % of Al_2O_3, 10 to 20% of CaO and having plagioclase, pyroxene as the major mineral components.

About 99% of chemical composition of the Lunar soil simulant of the present invention comprises of major oxides such as SiO_2 , Al_2O_3 , CaO, TiO_2, Fe_2O_3 , MgO, MnO, Na_2O, K_2O, P_2O_5 and remaining one percent are trace elements. Silica, aluminium, and calcium are the three major elements which cover almost 93-98% of anorthosite composition. The specified chemical composition of the present lunar simulant soil (LSS-ISAC-1) is shown in Table 1.

Table 1: Chemical composition of rock samples used for the purposes of the present invention "Anorthosite Rocks".

Oxides	Anothosite-1	Anorthosite-2	Average
SiO_2	44.70	46.33	45.52
TiO_2	0.03	0.05	0.04
Al_2O_3	30.41	29.24	29.82
Fe_2O_3	0.70	0.89	0.80
MgO	2.45	2.44	2.44
MnO	0.02	0.02	0.02
CaO	17.8	17.41	17.61
Na_2O	1.36	1.99	1.67
K_2O	0.01	0.01	0.01
P_2O_5	0.02	0.02	0.02
LOI	0.77	1.55	1.16
Total	98.27	99.95	99.11

Table 2: Specified chemical composition rock samples used for the purposes of the present invention "Anorthosite Rocks"

S. No.	Major Oxides	Major Oxides in Lunar Soil Simulant (LSS-ISAC-1) (in percentage)
1.	SiO_2	43-46
2.	Al_2O_3	21-31
3.	CaO	15-18

The mineral content and the textural relationships within the selected rock samples were studied under polarizing petrological microscope. The detailed analysis of minerals in thin section, micro-texture and structure are critical in precisely selection of source rock for present simulant production. The mineralogical characteristics show phaneric texture, with medium to coarse grained plagioclase minerals more than 80%. Overall the thin sections constitute less mafic content. Augite and hypersthene are primary mafic minerals in the thin section. Pyroxene crystals were prominent surrounded by hornblende. The accessory minerals are spinel, ilmenite, magnetite, rutile and sulfides of iron, which are mostly indistinct in thin section.

Table 3: Specified mineralogy in anorthosite rock samples used for the purposes of the present invention

Sl. No.	Major Minerals	Percentage of Minerals in Lunar Soil Simulant	Average percentage of Minerals in Simulant
1.	Plagioclase	81-95	89
2.	Pyroxene	1-9	4
3.	Other minerals	1-5	2 to 3

Another aspect of the present invention provides a process for the manufacture of Lunar Soil Simulant (LSS) comprising the steps of:

a) Obtaining terrestrial rock samples having 40-50% of SiO_2, 20 to 40 % of Al_2O_3, 10 to 20% of CaO, and plagioclase, pyroxene as the major mineral components;
b) pulverising the material into gradations of 30-80 microns/ 80-150 microns/ 150-300 microns/ 300-600 microns/ 600-1000 microns; and
c) mixing the samples of different gradations/fineness in specific ratios.

In particular, the present invention relates to production of lunar soil simulant exclusively for lunar highland region by using the naturally available anorthosite rocks and then pulverizing to a certain degree of fineness.

This innovative procedural production process consists of procuring bulk rock samples (satisfying mineralogical and chemical composition) which have to be pulverized to a certain specified degree of fineness and gradation and thereafter to be mixed in a specific scientific proportion to obtain a lunar soil simulant (LSS).

In an embodiment, the source rock for preparation of the simulant of the present invention is near Sittampundi village (67km from Salem) on the banks of Cauvery River in the state of Tamil Nadu, India. The Sittampundi complex is dominated by relatively pure calcic anorthosite (An_{80-100}) with less mafic minerals and contains layers or lenses of chromite, garnet-pyroxene, gabbro, hornblendite, peridotite, pyroxinite and anthopyllite *(Ashwal, 2000, Anbazhagan and Arivazhagan, 2009*). The An80-100 composition is more close to lunar highland soil and using such source rock for simulant improve the fidelity.

The big rock masses are fragmented into small pieces by manual labourers for loading and transport to crushing unit. During bulk production, the pulverizing unit is exclusively earmarked for simulant production and all other parallel activities are stopped to avoid any contamination. Similarly, before starting the process, the entire crushing chamber and surrounding units are cleaned. In course of production process, the particle size distribution is checked with hand sieves.

During the processes of pulverization, at a time two gradations can be obtained separately by fixing the desired sieve sets in the crushing unit. However, one set of production contains all particle sizes, which will be recycled for further crushing and separation. It is observed that the production rate is varying for different gradation processes.

The anorthosite rocks are pulverized to particles in the gradations of 30-80 microns/ 80-150 microns/ 150-300 microns/ 300-600 microns/ 600-1000 microns. It is seen from the values of evaluated properties that particle size has got significant influence on mechanical properties due to inter-particle forces at micro level. Hence, it

is essential to scientifically evaluate mixing proportions of different gradations to satisfy the requirements for a lunar soil simulant.

The actual lunar soil consists of only solid particles without air and water. Hence the most of engineering properties of the soil is governed by the inter particle adhesive and cohesive forces and interlocking mechanism. Hence the particle size distribution plays a vital role in simulating the soil mass.

The most important single parameter in simulation studies of *wheel-soil interaction* is the "drawbar pull" that the wheel of rover can develop. *(This is defined as the pull that can be developed from the traction of a given wheel on a given soil for a certain input torque).* The drawbar pull, slip and rolling resistance are the main criteria to describe the traction behaviour of Rover. The important and relevant soil parameters define the traction conditions are *"angle of internal friction/ cohesion/ shear deformation modulus/ cohesive modulus of deformation/ frictional modulus of deformation and sinkage exponent etc"*. To simulate mix proportions to give the desired soil properties, two other important properties like the coefficient of uniformity (C_U) and coefficient of curvature (C_C) are also required to be assessed as they describe the nature of particle distribution for given mass of LSS.

The three important parameters to describe the traction conditions are tyre parameters like ***optimal radius, width, and inflation pressure***. Both the bearing and tractive capacity of a soil are dependent on the shear strength of the soil. The shear strength parameters of the soil depend on ***angle of internal friction (Φ), cohesion (c) and shear deformation modulus (k).*** Bearing capacity with respect to trafficability depends in particular on settlement due to soil compaction under the vehicle weight. Sinkage parameters of the soil are influenced by cohesive modulus of deformation (k_c), frictional modulus of deformation (k_Φ) and sinkage exponent (n). However the bearing capacity is more predominantly governed by the settlement that occurs as a result of shear failure.

Lesser the size of the particle more is the cohesive forces at micro level which influence the mechanical properties at macro level. Hence simulating the gradation or fineness of the particles is a pre-requisite before simulating the soil mass. Therefore the suitable range of gradations have been selected for pulverising anorthosite rock before evaluating the Geo-mechanical properties based on testing procedures outlined in different IS codes of soil mechanics.

The other relevant soil parameters are “angle of internal friction, cohesion, shear deformation modulus, cohesive modulus of deformation, frictional modulus of deformation and sinkage exponent etc”.

For arriving at the optimal ratio, a comprehensive scientific study has been carried out on all technical properties like cohesion modulus of deformation, friction modulus of deformation, sinkage exponent, cohesion stress, angle of internal friction, shear deformation modulus & bulk density etc of different mixes. The variational features of these properties were assessed individually for all gradations of sizes. Thereafter a large number of mixing samples were prepared to find out all the above properties to understand the influence of size of gradation on each geo-mechanical property. It is to be noted that on the Moon the soil media is a *single phase system* i.e. consisting of only solid particles contrary to soil media on the earth which consist of *solids-water-air (i.e. three phase system).* It can be inferred that inter granular forces will be a prime governing criteria for realising different mechanical properties. Based on this systematic *sample studies* have been exhaustively carried out to work out an optimal proportion where in all the above seven properties could be matched on the principles of soil mechanics & terra mechanics.

The variation of different Geo-mechanical properties like cohesive modulus of deformation [kc (N/m^{n+1})], frictional modulus of deformation [kp (N/m^{n+2})], sinkage exponent [n], cohesion Stress [c (N/m^2)], angle of internal friction [deg[, Shear deformation modulus [m], and bulk density [kg/m^3] with the variation of the ratios of soil particles of different gradations and fineness is studied. By using technical logic

and scientific basis for pattern of variation of different Geo-mechanical properties, the inventors have arrived at the desired mix proportions of different gradations of soil such that various Geo-mechanical properties with the desired values. This exercise involves applications of principles of soil mechanics and Geo-technical engineering by duly considering the only inter particle adhesive/cohesive forces.

After separation of gradations (based on grain size) into the five different sample set (Table 4) different mix proportions were arrived at to simulate the Geo-mechanical properties of lunar soil. Each mix consists of all five gradations with percentage not less than 10%. The inventors arrived at the desired mix proportion which was found to have the desired geo-mechanical properties. A comparison of the mechanical properties of the soil simulants obtained by mixing different ratios of soils of different gradations is furnished in Table 5.

In an embodiment, the evaluation of mechanical properties of the soil simulant to arrive at the desired mixture involves the steps of:

i) Determining the physical characteristics of the lunar soil simulant like bulk density/grain size by sieve analysis etc for particle size gradation.

ii) Conducting direct shear test to estimate the cohesive stress, angle of internal friction and shear deformation modulus.

iii) Conducting plate load test (for different plate sizes) to estimate the sinkage exponent, cohesive and frictional modulus of deformations.

iv) Innovatively working out a suitable mix proportion for LSS which tallies with the physical and engineering characteristics similar to Apollo-16 soil sample.

The lunar soil stimulant of the present invention is characterized by a Cohesive modulus of deformation of about 1400 kc (N/m^{n+1}), a frictional modulus of deformation of about 820000 kp (N/m^{n+2}), a sinkage exponent, n of about 0.8 to 1.2, a Cohesion Stress, c (N/m^2) of about 100 to 1000, an Angle of internal friction (deg), of about 30 to 50, a Shear deformation modulus (m) of about 0.0178, and a Bulk density (kg/m^3) of about 1500.0.

As indicated in above paras, five basic samples have been prepared based on the grain size of particles as mentioned below,

Table 4: Grain size distribution of Anorthosite soil samples

Soil sample	Grain size (in microns)
Sample A	30-80
Sample B	80-150
Sample C	150-300
Sample D	300-600
Sample E	600-1000

Table 5: Geo-mechanical properties of trial mixes of Soil simulant samples

Soil sample		Mechanical Properties						
	Mix proportions A:B:C:D:E	Angle of internal friction Φ (Degree)	Cohesion "c" (N/m^2)	Shear deformation modulus k (m)	Cohesion modulus of deformation k_c (N/m^2)	Friction modulus of deformation k_Φ (N/m^2)	Sinkage component n	Bulk density (kg/m^3)
MSS 1	8:3:4:3:2	40.97	421	0.0009	955	760100	0.9	1450
MSS 2	8:3:3:3:3	36.34	353	0.0010	1029	822559	1.03	1500
MSS 3	3:3:3:3:8	39	300	0.0150	1035	822800	1.05	1520
MSS 4	3:3:4:6:4	38	320	0.0145	1029	822559	1.03	1510
MSS 5	7:4:3:3:3	37	360	0.0140	1020	822380	1.02	1495
MSS 6	7:4:4:3:3	37	360	0.0140	1025	822390	1.02	1495

The present invention provides a unique and inventive method for manufacturing and producing large quantities of lunar soil simulant which not only has chemical and mineralogical composition which is similar to the lunar soil, but also has strikingly similar mechanical and geotechnical properties to that of lunar soil. The method can be practiced at minimum possible cost – which will make a way for carrying out extensive research and development works either for "Lunar Locomotive Engineering" or for postulating broad design philosophy for realizing lunar Civil

Engineering structures–which is relevant and required in view of future Moon colonization and interplanetary engineering.

The following examples are provided to better illustrate the claimed invention and are not to be interpreted in any way as limiting the scope of the invention. All specific materials, and methods described below, fall within the scope of the invention. These specific compositions, materials, and methods are not intended to limit the invention, but merely to illustrate specific embodiments falling within the scope of the invention. One skilled in the art may develop equivalent materials, and methods without the exercise of inventive capacity and without departing from the scope of the invention. It is the intention of the inventors that such variations are included within the scope of the invention.

EXAMPLES

ANALYTICAL INSTRUMENTATION

Analytical Procedure For Evaluating Chemical Composition:

Chemical analysis was carried out at Wadia Institute of Himalayan Geology, Dehradun and Centre for Earth Science Studies, Trivandrum for X-ray Fluorescence analysis. The sample preparation and analytical methods are given CESS website (http://cess/res.in/facilities/central-laboratories/xrf.lab). The analyses were performed on fusion glass disks for major elements. Fused glass disk is prepared on a Claisse Fluxy instrument in the sample preparation lab of CESS. One gram of finely powdered sample is mixed with 5 gram of flux and fused in a platinum crucible.

In order to calculate the percentage of minerals in the present case, the CIPW norm calculation was adopted. In this estimation, a rock is chemically analyzed to determine the elemental constituents. In general, major elements are expressed as oxides in chemical analysis. The normative mineralogy of the rock is then calculated, based upon assumptions about the order of mineral formation and known phase relationships of rocks and minerals, and using simplified mineral formulas.

Procedure for determining Cohesion Stress(C), Angle Of Internal Friction (Φ), Shear Deformation Modulus (K)

Shear strength parameters (cohesion and friction angle) are mechanical parameters of a soil that have profound influence on ultimate bearing capacity, slope stability and trafficability. The most common way to characterize the shear strength of a soil is the Mohr-Coulomb failure criterion, which can be expressed as: $\boldsymbol{\tau = c + \sigma.\tan \Phi}$

Where $\boldsymbol{\tau}$ is the shear strength at failure on the failure plane, $\boldsymbol{\sigma}$ is the normal stress on the failure plane; **c** is the cohesion of the soil, and **Φ** is the angle of internal friction.

Direct shear test

This test is used to determine the cohesion ***c***, friction angle **Φ**, and undrained shear strength $\boldsymbol{\tau}$, of the soil. Results are typically best when direct shear tests are performed on dry sandy materials. In a direct shear test, a soil sample is confined within a rigid square container called a shear box-which is split into two horizontal halves. The top of the shear box is subjected to an applied normal load which in turn applies a normal stress σ to the soil specimen. While the normal load is being applied, a shear force is simultaneously applied to the top half of the soil box so that the soil will fail in shear. A minimum of three direct shear tests with varying normal loads are suggested to obtain accurate strength parameters. The strength parameters, c and Φ are then determined by plotting the maximum shear stress τ versus the corresponding normal stress σ for the direct shear test ensemble. Using a best-fit line to connect the test points on the resulting plot, the friction angle is defined as the angle of the best-fit line from the horizontal axis; while the cohesion is defined as the intercept of the best-fit line on the vertical axis. Further, the shear deformation modulus (K) is defined as the displacement corresponding to the $0.63\tau_{max}$ as schematically indicated in graph (Fig.5).

Cohesive Modulus Of Deformation (K_c), Frictional Modulus Of Deformation (K_φ), Sinkage Exponent (N)

The internal cohesion and friction between the soil particles affect the deformation of the soil under the normal loading. Further, the relation between the applied pressure and resulting deformation depends on sinkage exponent `n' that describes the trend followed by the deformation curve. Plate load test is used to find out these properties. The results of the plate load test allow for the prediction of vehicle sinkage and motion resistance to the compaction of the terrain.

Plate load test procedure

Size and Shape of Plate – The tests were conducted by using different aspect ratio (l/b) of plates where l and b are length and width of the plate respectively. The length of the plates has been kept constant and the width of the plate has been varied. The length of the plate is equal to the wheel diameter of the rover (180mm). The width of the plate has been taken with different values such that the aspect ratio of the plate will be 1, 1.5, 2.0, and 2.5 etc.

Test Tank Size - The size of the test bed has been finalized based on the minimum aspect ratio which is the critical for stress distribution. Accordingly, the approximate required size of the test tank has been taken as 0.75m x 0.75m x 0.75m. The amount of soil required for one plate load test has been calculated as 0.5 tons (5KN) assuming the unit weight of the soil as $15KN/m^3$.

Test Arrangement:

1. The test plate was placed over the LSS, so that the centre of plate coincides with the centre of reaction girder/beam with the help of a plumb and bob and then horizontally leveled by a spirit level to avoid eccentric loading. The hydraulic jack was centrally placed over the plate with the loading column in between the jack and reaction beam so as to transfer load to the plate. A ball and socket arrangement has been inserted to keep the direction of the load vertical throughout the test. A suitable minimum seating pressure was applied and removed before starting the load test.

2. Two supports of the reference beam or datum rod was placed over the tank wall, fixed with minimum two dial gauges resting at diametrically opposite ends of the plates. The dial gauges were so arranged that settlement is measured continuously without any resetting in between.

Load Increments - The loads were applied in a particular interval throughout the experiment. The loads were exerted without impact or fluctuation or eccentricity.

Settlement and Observation – The settlement of the plate was recorded through mechanical dial gauges. Then, the pressure-settlement results were plotted by using best fit curve, so that the values of k (deformation modulus) and n (sinkage co-efficient) can be obtained. The pressure-sinkage relationship used in this study is the equation proposed by Bekker (1969) as given in below:

$$P = kZ^n$$

Where k is a modulus of inelastic deformation, and n is the exponent of sinkage. This equation was found to be very limited in application as the value of k was dependent on the size and shape of the test plate and hence this may not be a true modulus of deformation. Therefore, Bekker has developed the Bernstein-Goriatchkin equation, which is applicable to any size or shape of plate. Bekker’s modified equation is written as,

$$P = (k_c/b + k)\ Z^n$$

Where P is the pressure and Z is the soil depth or sinkage as before, but k_c and k_Φ are modulus of deformation with respect to cohesion and friction. In order to process the experimental data, namely the pressure p and sinkage z curves, which have been obtained from the plate-load tests, were used to determine the terrain constants. Wong’s (1980) weighted “least squares method” is employed to arrive at these values. The schematic view of the plate load test and expected load-settlement plot is shown in Fig. 6. Best-fitted values of the pressure-sinkage terrain parameters are obtained by minimizing the following function using a weighting factor p^2,

$$F = \sum p^2 \left[\ln p - \ln\left(k_c / b + k_\varphi\right) - n \ln z\right]^2$$

Minimization of equation involves taking the partial derivatives of the function with respect to n and k where $k = (k_c/b + k_\Phi)$, and setting them equal to zero.

Solving the resulting equations simultaneously gives rise to the following equations for n and k.

$$n = \frac{\sum p2 \sum p2 \ln p \ln z - \sum p^2 \ln p \sum p^2 \ln z}{\sum p^2 \sum p^2 (\ln z)^2 - \left(\sum p^2 \ln z\right)^2}$$

$$\ln k = \frac{\sum p2 \ln p - n \sum p2 \ln z}{\sum p^2}$$

When using two different plate sizes a unique n is usually obtained for each. Therefore, it is required to use the average n-value resulting from the two different plates when calculating the natural logarithm of k in equation. However, since k = (k_c/b + k_Φ) there will be two resulting k -values: one for plate size b_1 and another for plate size b_2. Accordingly, the values of k_c and k_Φ were determined by plotting the graph between k and l/b ratio. Using a best-fit line to connect the test points on the resulting plot, the k_c is defined as the slope of the best-fit line from the horizontal axis; while the k_Φ is defined as the intercept of the best-fit line on the vertical axis shown in Fig.7

COMPARATIVE EXAMPLE:

The return samples from Apollo-16 mission provide the closest direct example of Lunar highland soil. Hence, the simulant of the present invention (named as LSS-ISAC-1) compared with the Apollo-16 soil with respect to its chemical composition, mechanical properties and fineness of grains.

Table 6: Chemical composition of “Lunar highland return samples” and “Anorthosites samples of the present invention”

Oxides	Lunar highland Samples			Anorthosite samples		
	Lunar Anorthosite 1	Lunar Anorthosite -2	Average	Anothosite -1	Anorthosite -2	Average
SiO_2	44.3	45.2	44.75	44.70	46.33	45.52
TiO_2	0.06	0.04	0.05	0.03	0.05	0.04
Al_2O_3	35.1	36.2	35.65	30.41	29.24	29.82
Fe_2O_3	0.67	0.61	0.64	0.70	0.89	0.80

MgO	0.80	0.31	0.55	2.45	2.44	2.44
MnO	-	0.13	0.13	0.02	0.02	0.02
CaO	18.27	14.5	16.4	17.8	17.41	17.61
Na_2O	0.80	2.20	1.5	1.36	1.99	1.67
K_2O	-	0.77	0.77	0.01	0.01	0.01
P_2O_5	-	0.00	0.00	0.02	0.02	0.02
LOI	-	-		0.77	1.55	1.16
Total	100.00	99.96	99.99	98.27	99.95	99.11

Table 7: Specified chemical composition in lunar anorthosites and lunar soil simulant

Sl. No.	Major Oxides	Major Oxides in Lunar Anorthosite samples –Apollo 16 (in percentage)	Major Oxides in Lunar Soil Simulant (LSS-ISAC-1) of the present invention	Remarks/ Inferences
1.	SiO_2	44-46	43-46	Very Closely tallies
2.	Al_2O_3	21-36	21-31	Closely tallies
3.	CaO	14-18	15-18	Closely tallies

Table 8: Specified mineralogy in lunar highland Anorthosite and lunar soil simulant

Sl. No.	Major Minerals	Percentage of major minerals in Lunar Anorthosite (Apollo 16 return)	Percentage of Minerals in Lunar Soil Simulant of the present invention	Average percentage of Minerals in Simulant	Remarks/ Inferences
4.	Plagioclase	80-91	81-95	89	tallies
5.	Pyroxene	4-20	1-9	4	tallies
6.	Other minerals	1-10	1-5	2 to 3	tallies

Table 9: Comparison of Mechanical Properties of Lunar Soil Simulant

Sl. No.	Soil properties	Lunar soil simulant (MSS-2) of the present invention	Reference values of Apollo-16 sample	Standard Deviation	Remarks/ Inferences
1	Cohesion modulus of deformation k_c (N/m^2)	1029	1400 (Approximate)	6.55	tallies
2	Friction modulus of deformation, k_ϕ (N/m^2)	822559	820000 (Approximate)	141.64	Closely tallies
3	Sinkage exponent, n	1.03	0.8 to 1.2	0.044	Closely matches
4	c -Cohesion stress, (N/m^2)	353	100 to 1000	8.055	In the range
5	Angle of internal friction, Φ (deg)	36.34	30 to 50	0.849	tallies
6	Shear deformation modulus, k (m)	0.0143	0.0178 (Approximate)	0.0003	tallies
7	Bulk density, (kg/m^3)	1500	1500 (Approximate)	1.63	Very closely matches

We claim:

1. A lunar soil simulant manufactured from terrestrial analogue rock comprising 40-50% of SiO2, 20 to 40 % of Al2O3, 10 to 20% of CaO, and plagioclase, pyroxene as the major mineral components, characterized in that
   40-50% of the soil particles have a particle size distribution of 30-80µm,
   15-20% of the soil particles have a particle size distribution of 80-150µm,
   15-20% of the soil particles have a particle size distribution of 150-300µm,
   15-20% of the soil particles have a particle size distribution of 300-600µm,
   15-20% of the soil particles have a particle size distribution of 600-1000µm.

2. A lunar soil simulant as claimed in claim 1, wherein the terrestrial analogue comprises of an anorthosite rock.

3. The lunar soil simulant as claimed in claim 1, wherein it comprises 5-10% of one or more of the metal oxides selected from Fe_2O_3, MgO, MnO, Na_2O, K_2O, and P_2O_5.

4. The lunar soil simulant as claimed in claim 1, wherein the percentage of plagioclase is 70-90% of the total mineral composition.

5. The lunar soil simulant as claimed in claim 1, wherein the percentage of pyroxene is 2-30% of the total mineral composition.

6. The lunar soil simulant as claimed in claim 1, having a Cohesive modulus of deformation of about 1400 kc (N/m^{n+1}).

7. The lunar soil simulant as claimed in claim 1, having a frictional modulus of deformation of about 820000 kp (N/m^{n+2}).

8. The lunar soil simulant as claimed in claim 1, having a Sinkage exponent, n of about 0.8 to 1.2.

9. The lunar soil simulant as claimed in claim 1, having a Cohesion Stress, c (N/m^2) of about 100 to 1000.

10. The lunar soil simulant as claimed in claim 1, having an Angle of internal friction (deg), of about 30 to 50

11. The lunar soil simulant as claimed in claim 1, having a Shear deformation modulus (m) of about 0.0178.

12. The lunar soil simulant as claimed in claim 1, having a Bulk density (kg/m^3) of about 1500.0.

13. A method for manufacture of a lunar soil simulant comprising the steps of:

    a) Obtaining a terrestrial rock sample having 40-50% of SiO_2, 20 to 40 % of Al_2O_3, 10 to 20% of CaO, and plagioclase, pyroxene as the major mineral components;

    b) pulverising the material into gradations of 30-80 microns/ 80-150 microns/ 150-300 microns/ 300-600 microns/ 600-1000 microns; and

    c) Mixing the samples of different gradations/fineness in specific ratios.

14. A method for manufacture of a lunar soil simulant as claimed in claim 13, wherein the terrestrial rock sample comprises an anorthosite rock.

15. The method as claimed in claim 13, wherein the anorthosite rocks are obtained from Sittampundi village in the state of Tamil Nadu, India.

16. The method as claimed in claim 13, wherein the ratio in which the materials of different gradations are mixed is:

    40-50% of the soil particles having a particle size distribution of 30-80µm,
    15-20% of the soil particles having a particle size distribution of 80-150µm,
    15-20% of the soil particles having a particle size distribution of 150-300µm,
    15-20% of the soil particles having a particle size distribution of 300-600µm,
    15-20% of the soil particles having a particle size distribution of 600-1000µm.

Dated this 15 day of May 2014

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ABSTRACT

LUNAR SOIL SIMULANT AND A PROCESS FOR ITS MANUFACTURE

The present invention relates to a lunar soil simulant prepared from a terrestrial analogue and a method for producing and manufacturing it. The simulant almost equivalent with regolith of lunar highland region and comparable with Apollo 16 return samples. The lunar soil simulant can be used for scientific studies of lunar terrain relating to mobility/ trafficability of rover for scientific explorations or for the study of geo-technical/ mechanical properties of lunar soil for understanding the engineering behavior of lunar regolith or to carry out fundamental research work (theoretical and experimental) to postulate a broad design philosophy for realizing civil engineering structures on Moon surface, and to make a pathway to lunar locomotive engineering.